North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea

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LONG-TERM GOALS

The North Pacific Acoustic Laboratory (NPAL) program is intended to improve our understanding of (i) the basic physics of low-frequency, broadband propagation in deep water, including the effects of oceanographic variability on signal stability and coherence, (ii) the structure of the ambient noise field in deep water at low frequencies, and (iii) the extent to which acoustic methods, together with other measurements and coupled with ocean modeling, can yield estimates of the time-evolving ocean state useful for acoustic predictions. The goal is to determine the fundamental limits to signal processing in deep water imposed by ocean processes, enabling advanced signal processing techniques to capitalize on the three-dimensional character of the sound and noise fields.

OBJECTIVES

A series of deep-water acoustic propagation experiments combining low-frequency, broadband sources with vertical and horizontal receiving arrays were conducted in the North Pacific Ocean during the period 1989 to 2005 as part of what is loosely referred to as the North Pacific Acoustic Laboratory

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(NPAL) (Worcester and Spindel, 2005). These experiments were designed to measure the spatial and temporal statistics of the fluctuations of resolved rays and normal modes. The results reflect the background sound-speed field, the low level of eddy variability, the small-scale sound-speed fluctuations caused by internal waves and density-compensated temperature and salinity variations (spice), and the noise sources found in the relatively benign northeast and north central Pacific Ocean.

During 2009–2011 the methods developed to study long-range, deep water broadband acoustic propagation in the North Pacific were applied to investigate deep-water acoustic propagation and ambient noise in the much more oceanographically and geologically complex northern Philippine Sea. Three experiments were conducted: (i) 2009 NPAL Pilot Study/Engineering Test (PhilSea09), (ii) 2010–2011 NPAL Philippine Sea Experiment (PhilSea10), and (iii) Ocean Bottom Seismometer Augmentation of the 2010–2011 NPAL Philippine Sea Experiment (OBSAPS).

In contrast to the oceanographically benign northeast and north central Pacific Ocean, the sound-speed field in the Philippine Sea is modulated by strong eddy variability moving in from the east (Qiu, 1999; Kobashi and Kawamura, 2002; Qiu and Chen, 2010). The westward-propagating eddies interact with an intense western boundary current, the Kuroshio, that flows northward to the east of Taiwan. Large internal tides generated in Luzon Strait between Taiwan and the Philippines and at the Mariana Island Arc to the east propagate into the region (Niwa and Hibiya, 2004; Jan *et al*., 2008; Zhao and D'Asaro, 2011; Kerry *et al*., 2012). Typhoons regularly cross the Philippine Sea during summer and fall, affecting the structure of the upper ocean.

The goals of the Philippine Sea experiments included (i) understanding the impacts of fronts, eddies, and internal tides on acoustic propagation, (ii) determining whether acoustic methods, together with other measurements and ocean modeling, can yield estimates of the time-evolving ocean state useful for making improved acoustic predictions and for understanding the local ocean dynamics, (iii) improving our understanding of the physics of scattering by internal waves and spice (density-compensated temperature and salinity variations), (iv) characterizing the depth dependence and temporal variability of the ambient noise field, and (v) understanding the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals.

APPROACH

PhilSea09. A short-term Pilot Study/Engineering Test was conducted in the Philippine Sea during April-May 2009. A single acoustic path, approximately corresponding to one of those to be instrumented during the 2010–2011 PhilSea10 experiment, was instrumented with a moored, broadband source (T1) and a prototype Distributed Vertical Line Array (DVLA) receiver. Both moorings remained in place for about one month, while coordinated, ship-based measurements were made. These included transmissions to the DVLA from J15-3 (Groves, 1974; Young, 1975) and MP-200 (Andrew, 2009) sources suspended from shipboard and recording of the T1 and ship-suspended source transmissions by the towed Five Octave Research Array (FORA) (Becker and Preston, 2003). The range (WGS84) from the reference position of the DVLA to the reference position of mooring T1 was 185.127 km.

The moored source was a Teledyne Webb Research swept-frequency acoustic source that transmitted linear frequency-modulated (FM) signals extending from 225 to 325 Hz and lasting 135 s (Webb *et al*., 2002; Morozov and Webb, 2003, 2007). The median source depth was 1098.6 m.

The DVLA consisted of two 1000-m subarrays: an *axial subarray* spanning the sound-channel axis and a *deep subarray* spanning the surface conjugate depth. A D-STAR (DVLA – Simple Tomographic Acoustic Receiver) controller located at the top of each subarray provided timing and scheduling for distributed, self-recording Hydrophone Modules that were clamped to the mooring wire (Worcester *et al*., 2009). Inductively coupled modems provided low-bandwidth (1200 baud) communication between the D-STAR controllers and the Hydrophone Modules over standard oceanographic mooring wire for command, control, and time synchronization. Each subarray contained 30 Hydrophone Modules.

PhilSea10. The 2010–2011 NPAL Philippine Sea deep-water acoustic propagation experiment combined measurements of acoustic propagation and ambient noise with the use of an ocean acoustic tomography array to help characterize this oceanographically complex and highly dynamic region. A full water-column-spanning DVLA consisting of five 1000-m subarrays, with a combined total of 150 Hydrophone Modules, was deployed within an array of six broadband acoustic transceivers (T1-T6) from April 2010 until March-April 2011 (Fig. 1). All six of the moored sources were Teledyne Webb Research swept-frequency acoustic sources similar to the source deployed during PhilSea09. The median source depths were 1060–1070 m. The DVLA recorded the transmissions from the six sources in order to study acoustic propagation and scattering. Each acoustic transceiver also recorded the transmissions from the other transceivers, forming a six-element ocean acoustic tomography array with a radius of approximately 330 km. The tomographic measurements, when combined with satellite, glider, and other in situ measurements and with ocean models, will provide an eddy-resolving, 4-D sound-speed field for use in making acoustic predictions.

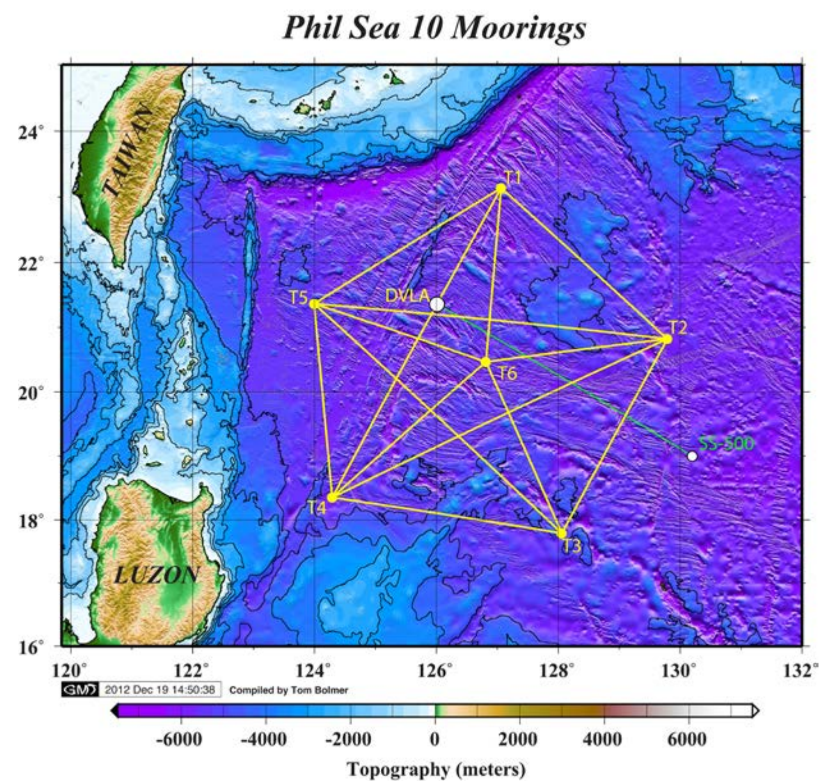

Figure 1. Geometry of the PhilSea10 experiment. A Distributed Vertical Line Array receiver was moored at DVLA. Broadband acoustic transceivers were moored at T1-T6. Ship-suspended sources transmitted to the DVLA from ship station SS-500.

During May 2010 MP-200 Multiport and HX-554 (ATOC Instrumentation Group, 1995) sources suspended from shipboard at ship station SS-500 transmitted to the DVLA (Andrew *et al*., 2010). During July 2010 a J15-3 source suspended from shipboard transmitted to the DVLA at fixed locations approximately one-half and one convergence zone from the DVLA and during a number of tows.

Four acoustic Seagliders were deployed during November 2010 in the vicinity of the PhilSea10 moored array (Howe *et al*., 2011; Van Uffelen *et al*., 2012). The gliders measured temperature and salinity in the upper 1000 m of the ocean between the moorings and recorded the transmissions from the moored acoustic sources. A major objective was to determine whether, given the joint nature of the combined navigation/tomography problem, it is possible to use Seagliders equipped with an Acoustic Recorder System (ARS) as mobile nodes in a tomographic array, thereby enhancing the resolution of the tomographic system.

OBSAPS. A near-seafloor, 1000-m long O-DVLA (OBSAPS-DVLA), with a total of 15 Hydrophone Modules, and an array of five ocean bottom seismometers (OBS) were deployed in the Philippine Sea during April-May 2011, immediately following recovery of the PhilSea10 moorings, to study the relationship between the acoustic field in the water column and the seismic field in the seafloor for both ambient noise and signals transmitted by a ship-suspended J15-3 source (Stephen *et al*., 2011). The O-DVLA and OBS remained in place for approximately one month.

WORK COMPLETED

Post-cruise Calibrations. The Teledyne Webb Research acoustic sources, the thermistors in the Hydrophone Modules, and the pressure sensors in the D-STAR controllers and STAR source controllers have all been calibrated following completion of the PhilSea10 and OBSAPS experiments. The Webb sources were calibrated at the Seneca Lake Sonar Test Facility during July 2011. The testing revealed that the source levels varied substantially with frequency across the band. The average transmitted power levels were therefore significantly less than the maximum source levels. In addition, the transmitted waveforms deviated significantly from an ideal linear FM signal, requiring that the actual measured waveforms be used for signal processing (pulse compression).

The Hydrophone Module thermistors and the D-STAR/STAR pressure sensors were calibrated at the SIO Calibration Facility. The postcruise Hydrophone Module thermistor calibrations typically differed from the precruise calibrations by less than ± 0.005°C.

Analysis. Analyses of the PhilSea09, PhilSea10, and OBSAPS data sets continued throughout FY11 and FY12. Reprocessing and retracking of the resolved ray arrivals using the actual transmitted signal as measured at Seneca Lake have been completed for the PhilSea09 DVLA data. The PhilSea10 data recorded by the DVLA and transceivers T1-T6 still need to be reprocessed and retracked.

A special issue of the *Journal of the Acoustical Society of America* entitled “Deep-water Ocean Acoustics” is in preparation. P. Worcester (SIO) and J. Colosi (NPS) are the guest editors for the special issue. A number of NPAL-related manuscripts have been submitted (Chandrayadula *et al*., 2012a, b; Colosi, 2012; Colosi *et al*., 2012a,b; Dzieciuch *et al*., 2012; Farrell and Munk, 2012; Freeman *et al*., 2012; Heaney *et al*., 2012; Henyey *et al*., 2012; Powell *et al*., 2012; Stephen *et al*., 2012; Van Uffelen *et al*., 2012; White *et al*., 2012). The special issue is expected to go to press in early 2013.

D-STAR2 Development. We have begun a small-scale design effort to develop a simpler, smaller, and cheaper DVLA controller employing the Symmetricom Chip-scale Atomic Clock (CSAC) that recently became available. The CSAC eliminates the need for the complex dual-oscillator system currently employed in the D-STAR. The existing system has a precise, but high power, rubidium oscillator that is turned on once a day to check the frequency of a less precise, but low power, Q-Tech Microcomputer Compensated Crystal Oscillator (MCXO). Our tests have shown that that CSAC meets its specifications and will provide adequate timing precision without the need for a two-oscillator system.

RESULTS

2010–2011 NPAL Philippine Sea Experiment (PhilSea10). Processing of the LFM transmissions from the Teledyne Webb Research swept-frequency sources as recorded on the DVLA yielded acoustic time fronts spanning almost the entire water column with high signal-to-noise ratios at ranges from 129.355 km (T6) to 450.131 km (T3) (Fig. 2).

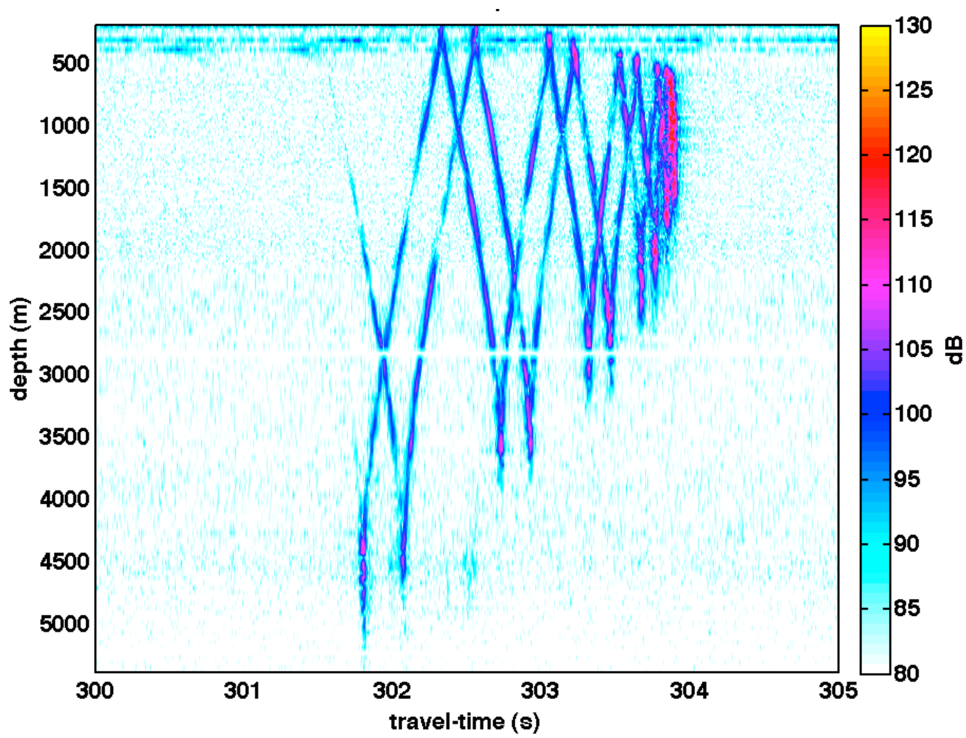

Figure 2. Acoustic time front on the DVLA for a transmission from the acoustic source on mooring T3 during PhilSea10. The recording was made on 27 April 2010 at 12:18:00 UTC.

During PhilSea10 the DVLA did not record any noise-only receptions. Nonetheless, it provided information on ambient noise levels for frequencies outside the band occupied by the signals transmitted by the moored sources. The *minimum* omnidirectional ambient noise levels observed at the DVLA decrease significantly below the surface conjugate depth at frequencies from 50 to 500 Hz (Fig. 3). Similar behavior had previously been observed in the central North Pacific (Shooter *et al*., 1990; Gaul *et al*., 2007), although the decrease observed in the North Pacific was significantly greater than that in the Philippine Sea. The minimum noise levels presumably correspond to times when there are

no nearby ships, wind speeds are low, and surface conditions are calm, so that there is little locally generated noise.

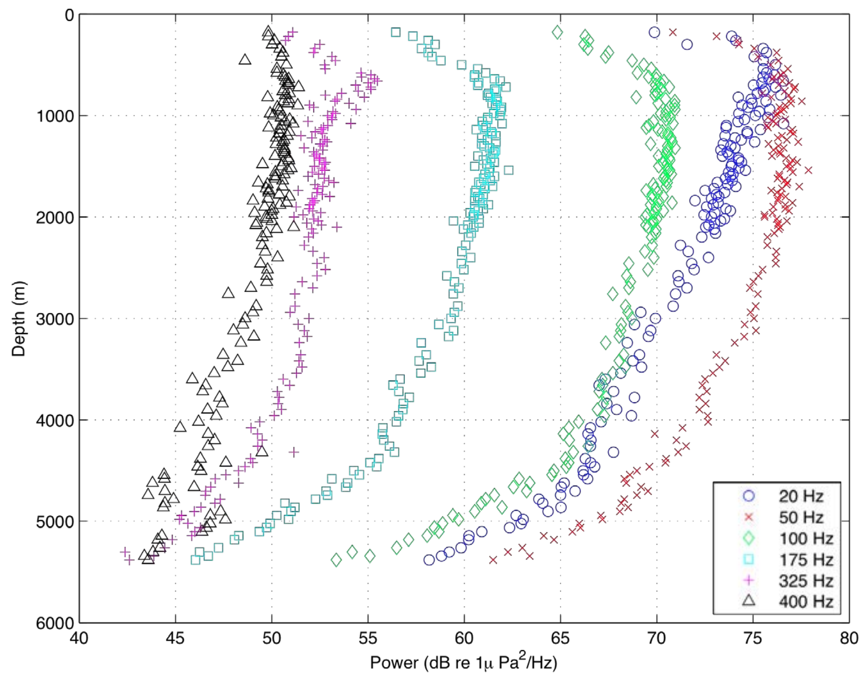

Fig. 3. Minimum omnidirectional ambient noise levels at six frequencies observed on the DVLA during PhilSea10 as a function of depth. These spectra are from the receptions of the T1 transmissions at 0000Z on every other day throughout the year (164 receptions).

Finally, the thermistors in the DVLA Hydrophone Modules provided temperature profiles spanning nearly the full water column (Fig. 4). These data will be used both to help characterize the oceanographic variability in the region and to construct sound-speed profiles for use in beamforming of the DVLA data.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior.

RELATED PROJECTS

A large number of investigators have been involved in research related to the NPAL project during this period, including R. Andrew (APL-UW), A. Baggeroer (MIT), M. Brown (UMiami), R. Campbell (OASIS), T. Chandrayadula (NPS), J. Colosi (NPS), G. D'Spain (MPL-SIO), B. Dushaw (APL-UW), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (Univ. Hawaii), J. Mercer (APL-UW), V. Ostachev (NOAA/ETL), B. Powell (Univ. Hawaii), S. Ramp (SOS), R. Stephen (WHOI), I. Udovydchenkov (WHOI), L. Van Uffelen (SIO), A. Voronovich (NOAA/ETL), and K. Wage (George Mason Univ.).

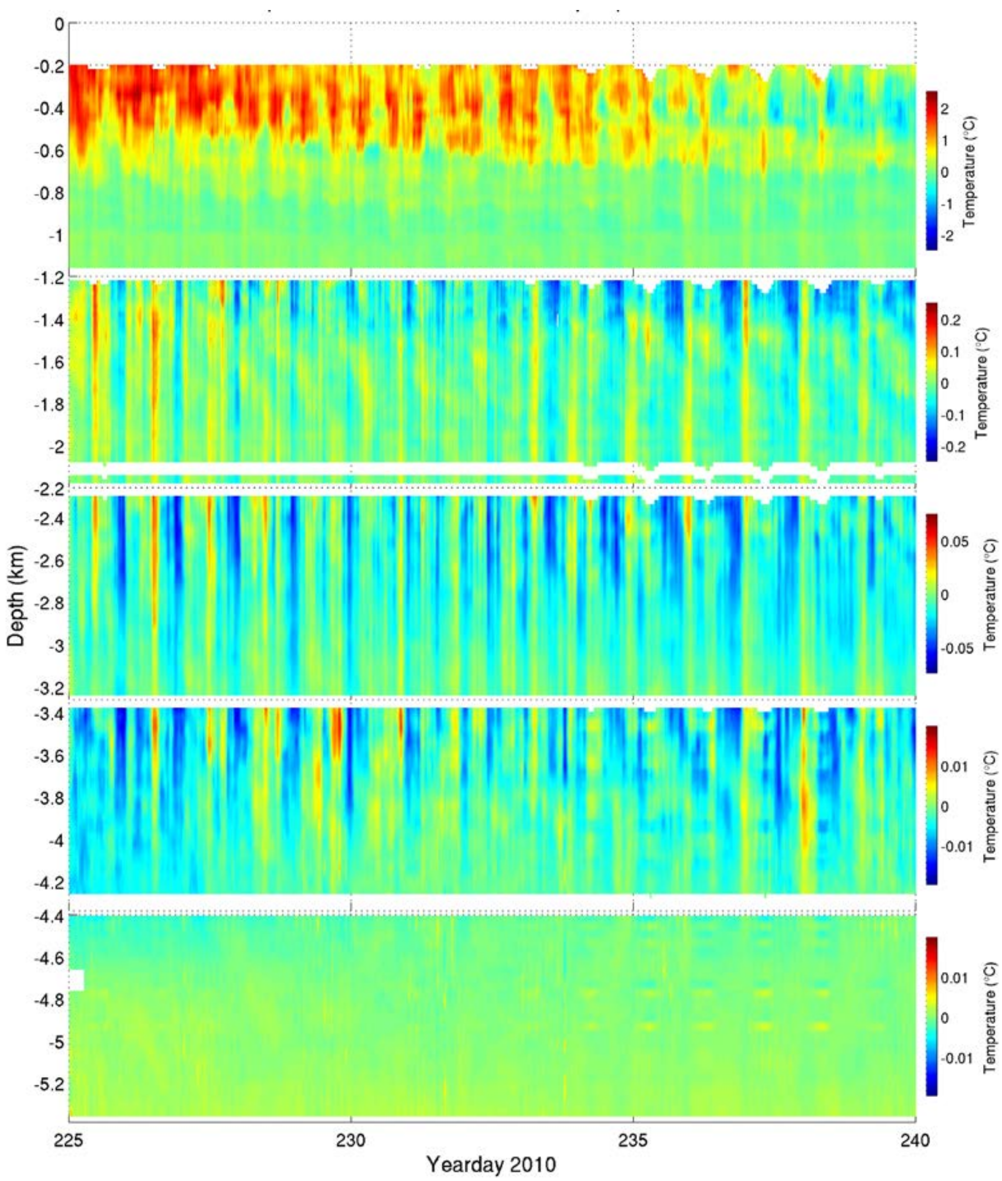

Figure 4. Temperatures for year days 225–240 from the DVLA Hydrophone Modules, with the time means removed. The thermistors warmed up by about 10 m°C during the acoustic receptions due to the heat generated by the electronics, and a first order correction has been applied to remove this signal.

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HONORS/AWARDS/PRIZES

Walter Munk: 50 Years/50 Leaders, One of UCSD's 50 alumni leaders who are transforming the world (18 June 2011)

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Walter Munk: Walter Munk Library on Chikyu, Japan (05 November 2012)